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MEASUREMENTS OF HEADPHONE TRANSFER FUNCTIONS (PTFs) ON 40 HUMAN SUBJECTS

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Introduction

Binaural signals, usually artificial head recordings, are specifically suitable for headphone reproduction. In this investigation data are collected with the purpose of obtaining correct reproduction of binaural signals through headphones. However, the data will be relevant for most situations where sound is reproduced through headphones.

The binaural technique is based on the following idea. The input to the hearing consists of two signals: sound pressures at each of the eardrums. If these are recorded in the ears of a listener and reproduced exactly as they were, then the complete auditive experience is assumed to be reproduced, including timbre and spatial aspects. In this technique effective separation of the two channels is essential and among the means for sound reproduction, only headphones offer this.

Normally, headphones for reproduction of traditional stereo recordings are suited for replicating either free field or diffuse field listening. However, for use in binaural technique the design goal is a flat frequency response from voltage at the headphone terminals to the recording point in the ear canal - denoted the reference point. For the purpose of comparing results the definition of the reference point is critical.

A thorough description of the measurements is given in Møller et al. [1] whereas this paper only describes the most important aspects. Among these is the choice of the point in the ear canal where the recording is made - the reference point. In the present investigation the choice of reference point is based on a model for the total transmission from a sound source to the listener's eardrums in a binaural system described by Møller [2]. The transmission during headphone playback is illustrated in the model given in Figure 1.

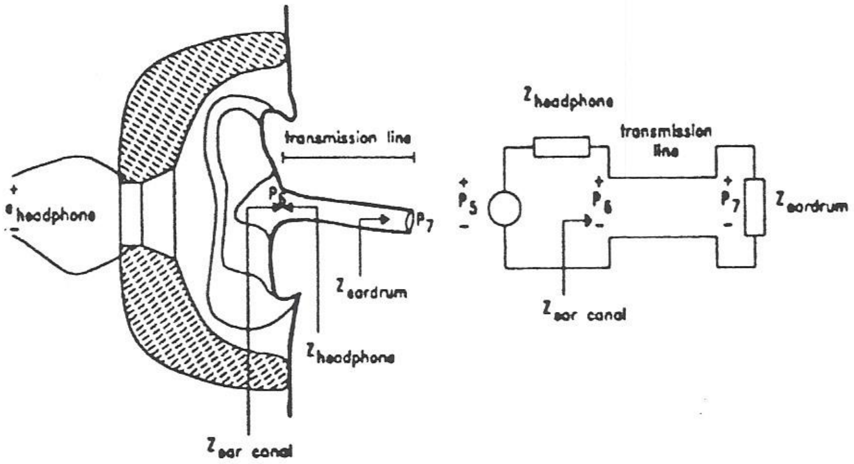

Figure 1. Left side: anatomical sketch of the headphone and the human external ear. Right side: equivalent model as described by Møller [2].

The voltage at the headphone terminals is called $e_{headphone}$. p_6 is the sound pressure at the entrance to the ear canal which acts like an acoustical transmission line terminated by the eardrum impedance $Z_{eardrum}$. At the eardrum, the sound pressure is denoted p_7. The headphone is modelled by the Thevenin sound pressure at the entrance to the ear canal, p_5. This sound pressure does not normally exist physically, but if the ear canal is blocked, for example with an earplug with its outer end flush with the entrance to the ear canal, p_5 is found at the outer side of the earplug. Note, that p_1-p_4 represent sound pressures in the recording situation and they are therefore not seen in Figure 1 (see [2], [3]).

Binaural recordings may be made at any point in the ear canal. However, the Thevenin sound pressure has some advantages [2],[3] and has been chosen in our investigation on binaural technique. With this choice the equalization needed for correct total sound transmission includes $[P_5/E_{headphone}]$ (see [2]). In this paper $[P_5/E_{headphone}]$ is denoted *headPhone Transfer Function (PTF)* (in order to avoid confusion with Head-related Transfer Function, HTF). The PTF reflects the headphone as well as the subject's external ear. The goal of this investigation is therefore to determine PTFs for a number of commercially available headphones, measured on a large number of subjects.

Correct total sound transmission also requires knowledge about the pressure division $[P_6/P_5]$ seen between $Z_{headphone}$ and $Z_{ear\ canal}$. If this pressure division is equal to the corresponding division during recording, where $Z_{headphone}$ is replaced by the free field radiation impedance, the equalization is especially simple. Information about the free field pressure division is available from a parallel work in our laboratory [3].

Method

The microphone techniques used for p_5 and p_6 measurements are sketched in Figure 2.

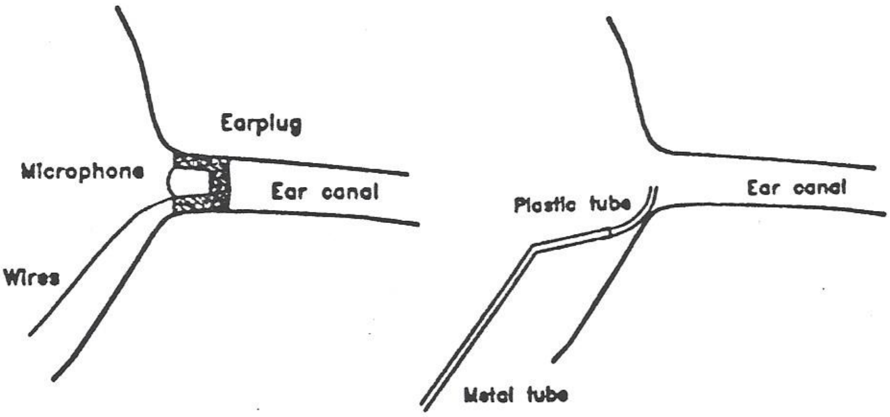

Figure 2. Left, p_5 measurement: miniature microphone inserted in an earplug in the ear canal. Right, p_6 measurement: tip of probe microphone at ear canal entrance.

The left sketch shows measurement of p_5 using a miniature microphone placed in a hole in an earplug. The end of the earplug and the microphone were mounted flush with the ear canal entrance.

A probe microphone was used for p_6 measurements. The right sketch above shows the metal probe tip extended by a small, individually fitted, piece of flexible plastic tube. The microphone was attached to the subject's pinna with a metal strap and fixed along the subject's neck with tape to avoid displacements.

To reduce the post processing of data needed for determination of the pressure division p_5 was also measured with the probe microphone. An earplug was inserted into the ear canal with its outer end flushing the ear canal entrance. The plastic probe tube was then carefully placed along the earplug surface with the tip near the center of the ear canal entrance. However, the miniature microphone can be placed more accurate for p_5 measurements and in addition with a better signal to noise ratio. Therefore p_5 measurements with the probe microphone are only used for determination of the pressure division.

The measuring setup is sketched in Figure 3. As it is seen both ears were measured simultaneously with two synchronized MLSSA measuring systems which are based on Maximum Length Sequence (MLS) technique. This method is basically noise immune, and combined with averaging the resulting signal to noise ratio is typically 70 dB for measurements with the miniature microphone and 60 dB with the probe microphone. The MLS length used was 4095 points and the recording was pre-averaged 16 times. With the sampling frequency 48 kHz the total time for each single measurement was only 1,45 s.

For determination of the pressure division $[P_6/P_5]$, the measured impulse responses to p_5 and p_6 were Fourier transformed followed by a complex division in the frequency domain. As the same equipment was involved for measurement of p_5 and

p_6 the influence of the equipment cancels out.

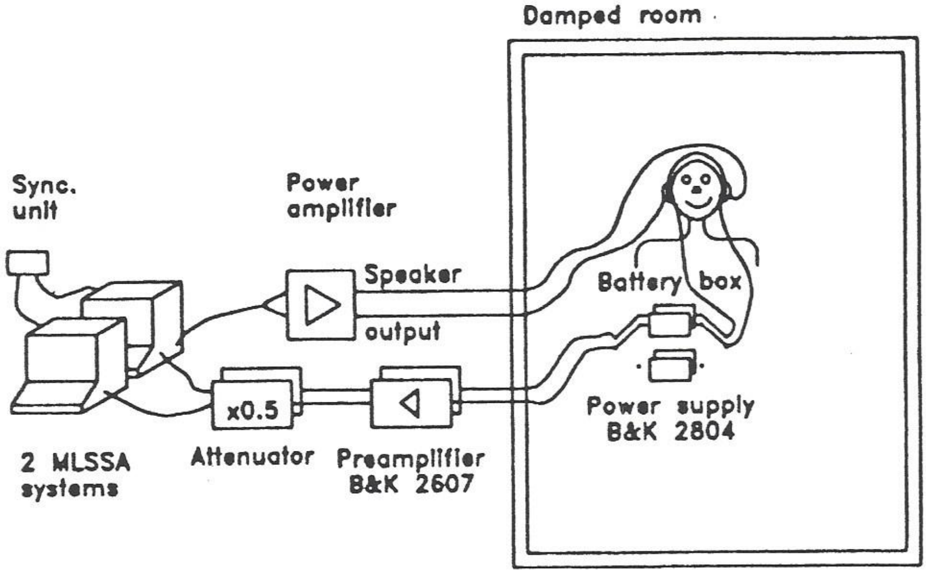

Figure 3. Sketch of the measuring setup.

It is slightly more complicated to find $[P_5/E_{headphone}]$. By Fourier transformation of the measured impulse response to p_5 the unwanted transfer function of the miniature microphone is included. By measuring the pressure response of the miniature microphone with a B&K 4136 microphone as reference, followed by complex division in the frequency domain, this error is removed.

Results

PTFs and pressure division was measured with 14 headphones on 40 human subjects - 18 females and 22 males. In Figure 4 PTFs for all the headphones are shown for both ears of one subject. An overall observation is that the responses vary considerably, even for the headphones which are claimed to follow a diffuse field characteristic (indicated by "DF" in Figure 4).

For the purpose of reproducing binaural signals a flat response measured at the reference point is desirable. At least the response should be easy to equalize, that is free from severe peaks and dips. Headphones number 5, 8, 11 and 12 are seen to meet this requirement while some seem difficult to equalize.

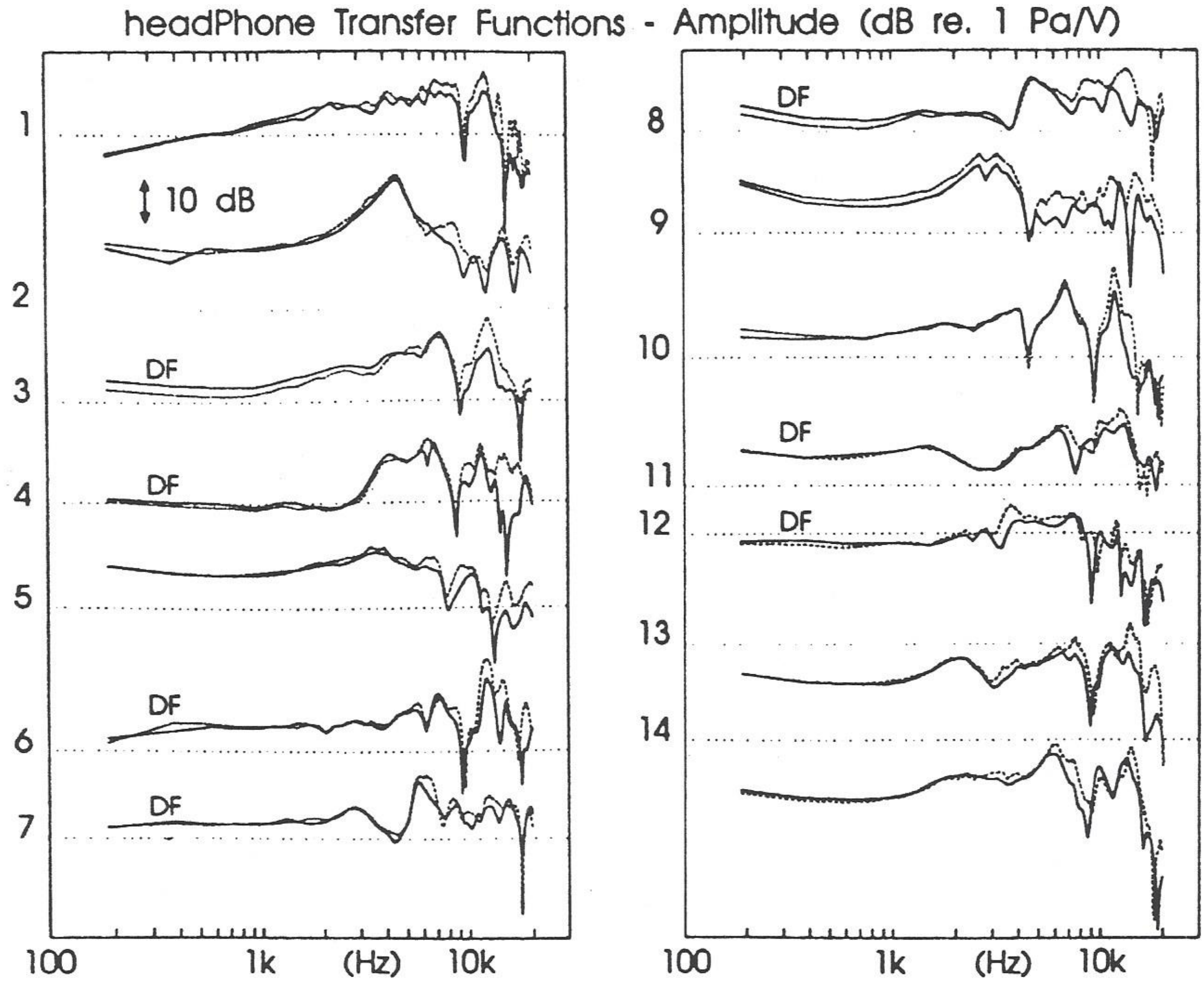

Figure 4. PTFs for the 14 headphones all measured on the same subject. PTFs for right ear are shown with dashed line. "DF" indicate that the headphone is claimed to follow a diffuse field characteristic.

In Figure 5 the upper set of curves shows the pressure division for all headphones, measured on the left ear of one subject. The lower set of curves in Figure 5 shows the corresponding free field pressure division, measured with sound incidence from 5 directions on the left ear of the same subject. As it is seen, the pressure division is generally comparable to the free field situation, although a few headphones seem to deviate. This means that in general headphones are "open", and therefore the PTF contains full information about the equalization needed to obtain correct transmission in a binaural recording/playback system.

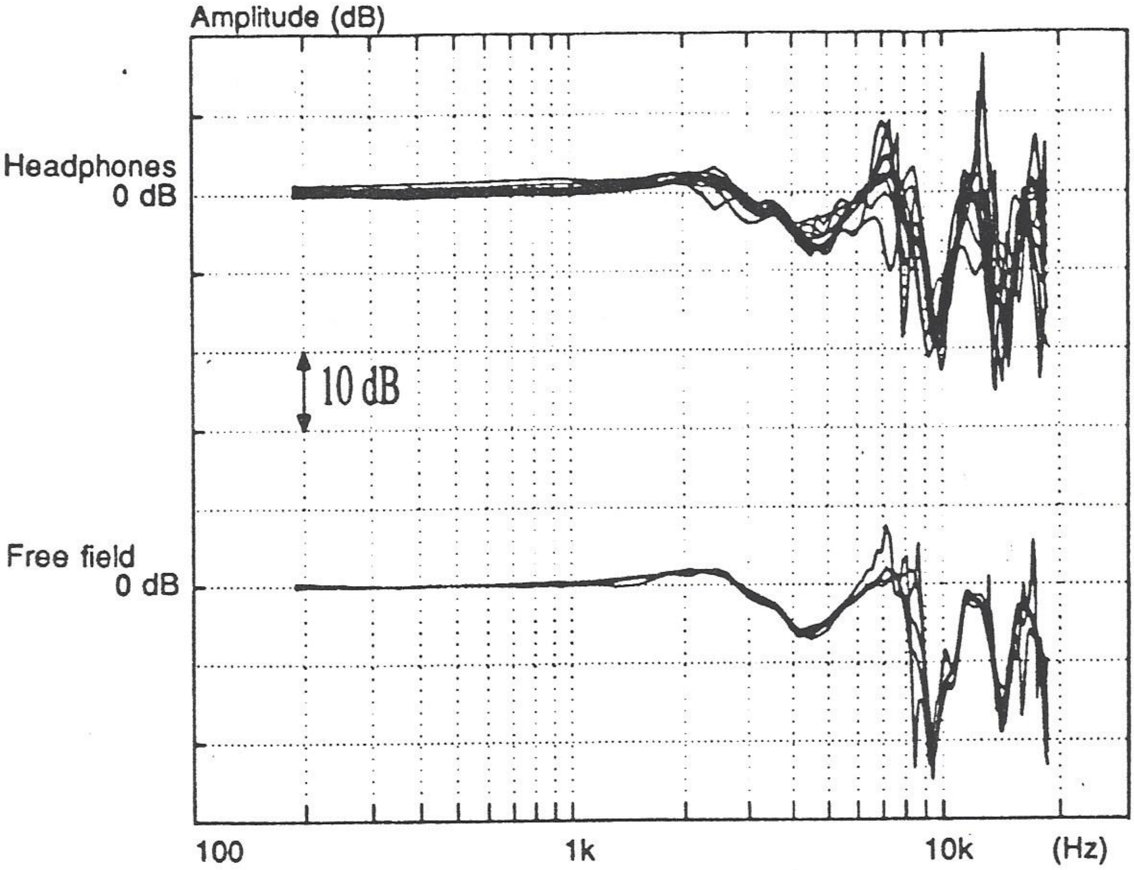

Figure 5. Upper curves show the pressure division for all headphones, measured on the left ear on one subject. Lower curves show the corresponding free field pressure division with sound from 5 directions for the same ear of the same subject (data from Hammershøi et al. [3]).

Conclusion

PTF data are measured, using Maximum Length Sequence (MLS) technique, on both ears of 40 human subjects with 14 commercially available headphones. The reference point for the measurements is at the entrance to the blocked ear canal. Data reveal considerable variation between headphones - even among headphones claimed to follow a diffuse field characteristic. Further measurements indicate that most headphones are "open", that is give the same acoustical load of the ear as free field listening. This is important for equalization in binaural systems.

References

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